

EARS Buoy Applications by LADC: I. Marine Animal Acoustics

George E. Ioup, Juliette W. Ioup, Lisa A. Pflug, and Arslan M. Tashmukhambetov

Department of Physics

University of New Orleans

New Orleans, LA 70148 USA

Natalia A. Sidorovskaya and Philip Schexnayder

Physics Department

University of Louisiana at Lafayette

Lafayette, LA 70504-4210 USA

Christopher O. Tiemann and Alan Bernstein

Applied Research Laboratories

University of Texas at Austin

Austin, TX 78713-8029 USA

Stan A. Kuczaj and Grayson H. Rayborn

University of Southern Mississippi

Hattiesburg, MS 39406 USA

Joal J. Newcomb*

Naval Oceanographic Office, Oceans Projects Department

Stennis Space Center, MS 39529 USA

Rowena Carlson

SPAWAR Systems Center Pacific

San Diego, CA 92152 USA

Alexander Ekimov

National Center for Physical Acoustics

University, MS 38677 USA

* formerly of Naval Research Laboratory, Stennis Space Center, MS

Abstract-Littoral Acoustic Demonstration Center (LADC) scientists have investigated sperm and beaked whale clicks as recorded on Environmental Acoustic Recording System (EARS) buoys to analyze whale behavior and the possibility of identifying individual whales acoustically. The research began in 2001 and continues through the present. LADC has conducted three experiments in the northern Gulf of Mexico and participated with the Naval Undersea Research Centre with three experiments in the Ligurian Sea. Initially the research centered on sperm whale coda clicks and echolocation clicks. In 2007 it was extended to the study of beaked whale echolocation clicks. The measured data suggest that click properties can be used to identify individual whales. Initially the identifications were done by grouping clicks using self-organizing maps and other means of cluster analysis. Each cluster or class represents an individual whale. These methods have been refined and have become reasonably robust. Verification of the identification has been a problem since using visual observations has not been satisfactory. Presently localization of the clicking animals is being coupled with cluster analysis to verify the identifications. A new finding that rhythms of echolocation clicks can be used to identify sperm whale individuals is now a part of the research, and cluster analysis, rhythm analysis, and localization are mutually reinforcing the identifications. Other results using EARS buoys for marine animal acoustics are listed among the key findings of LADC acoustic research.

I. INTRODUCTION

A consortium of scientists formed the Littoral Acoustic Demonstration Center (LADC) in 2001 to study ambient noise, propagation, and marine mammal acoustics in shallow water using Environmental Acoustic Recording System (EARS) buoys. The consortium now includes scientists from the University of New Orleans, the University of Southern Mississippi, the University of Louisiana at Lafayette, the Applied Research Laboratories of the University of Texas at Austin, the Naval Research Laboratory at Stennis Space Center, and the Naval Oceanographic Office at Stennis Space Center. Other scientists have been associated for specific projects.

Research supported by SPAWAR and ONR.

EARS buoys were developed as autonomous moored underwater recording systems by the Naval Oceanographic Office (NAVOCEANO) to make long-term ocean ambient noise measurements. When LADC was formed, the buoys were capable of measuring up to 1000 Hz for one year. When LADC added listening to sperm whales to its noise and propagation measurement missions, NAVOCEANO quickly modified the buoys to measure up to 5859 Hz for 36 days. The buoys, moored at depths from 550m to 950m in the Gulf of Mexico, produced exceptionally clear recordings of sperm whale echolocation and coda clicks and recordings of other whales. EARS Generation 2 buoys are now capable of recording one channel to 96 kHz, or 4 channels to 25 kHz, for more than 13 days on four 120 GB notebook disk drives. Experiments in the Gulf of Mexico and the Ligurian Sea have targeted both sperm and beaked whales. Audio results and visualizations of these recordings reveal rich detail of *Odontocete* clicks and enable new analyses such as the identification of individual whales from the properties of their clicks.

Beginning with experiments in 2001, LADC scientists have studied sperm whale clicks and clicking behavior. In 2007 the study was extended to beaked whale clicks. In part, the study of sperm whale clicks centered on identifying individual sperm whales from their coda clicks or echolocation clicks. These results fall into three categories. The first is the use of cluster analysis to group clicks from each individual. This has been applied both to coda and echolocation clicks. The second is the analysis of echolocation click rhythms to separate the echolocation clicks of different individuals. The third is the use of localization to verify the identifications produced. Cluster analysis has also been applied to beaked whale echolocation clicks, and research applying rhythm analysis and localization is now underway. Previous analysis of sperm whale clicks is reported in [1] – [5]. The work of the authors in whale click analysis has been reported in [6] – [29].

II. LADC MARINE MAMMAL ACOUSTIC EXPERIMENTS

LADC has led or participated in six experiments for the study of marine mammal acoustics. They are:

- 1) LADC 01 – Gulf of Mexico
- 2) SIRENA 02 – Ligurian Sea w/ NURC
- 3) LADC 02 – Gulf of Mexico
- 4) SIRENA 03 – Ligurian Sea w/ NURC
- 5) ZIPHIO 06 – Ligurian Sea w/NURC
- 6) LADC 07 – Gulf of Mexico

Experiments 1, 3, and 6 were performed by LADC, and the remaining experiments were led by the NATO Undersea Research Centre (NURC) with LADC participation. All experiments used EARS buoys.

- 1) LADC 01
 - Northeastern Gulf of Mexico
 - July 16 through Aug 21, 2001. The acoustic recordings spanned 36 days.
 - Buoys moored upslope off mouth of Mississippi River in water depths of 600m, 800m, 1000m.
 - Buoys moored 50 m above bottom.
 - During the experiment, Tropical Storm Barry passed within 100 nmi of the EARS buoys.
- 3) LADC 02
 - North central Gulf of Mexico
 - August 19 through September 15 planned, retrieval 23-24 October, 2002; 22 to 57 days recorded.
 - Buoys moored upslope off mouth of Mississippi River in water depths of 600m, 800m, 1000m.
 - Buoys moored 50 m above bottom.
 - Tropical Storm Isidore passed with 73 nmi of the EARS buoys, and Hurricane Lili passed within 116 nmi.

LADC 01 and LADC 02

- 3 Single Channel G1 EARS Buoys
- 11.7 kHz sampling rate

- 6) LADC 07
 - Gulf of Mexico south of Atchafalaya Bay at 1000m contour
 - July 3 - July 14, 2007
 - 6 Single Channel G2 EARS buoys on bottom-mounted moorings
 - 750-800m hydrophone depths
 - 192kHz sampling rate
 - 2.2 TB recorded (9 days, ~¾ capacity)

Fig. 1 shows the location of the LADC 01 and LADC 02 experiments. Figs. 2 and 3 show the location of the LADC 07 experiment. The asterisks in Fig. 3 denote the positions of the buoys. The northern buoys were spaced about 2.5 km apart in an attempt to detect single clicks on multiple buoys. The southern group was spaced at 5 km to increase total detection area.

Fig. 4 shows an analysis of 1 min of data from LADC 01. This minute is very rich in sperm whale clicks, including 15 codas. The top graph shows the amplitude versus time in sec. The middle graph is a spectrogram showing all frequencies up to the maximum of 5859 Hz. The bottom spectrogram shows from 0 to 1000 Hz. It makes clear the received acoustic signal from a

seismic airgun 107 km away. The airgun was fired approximately every 11 sec, and the red peaks and following tails are the first arrival and reverberations from the airgun. Fig. 5 extracts two four-second periods from the 1 min of Fig. 4. The expanded graphs show codas that are groups of 6 to 15 fairly regularly spaced clicks. These coda signals are used for communication by sperm whales. What is notable is that all the clicks in a particular coda appear to have very similar spectra with nulls consistently occurring in all the clicks of that coda. This pattern can vary from coda to coda. It is these spectrograms that suggest that properties of the clicks might be used to identify individual whales.

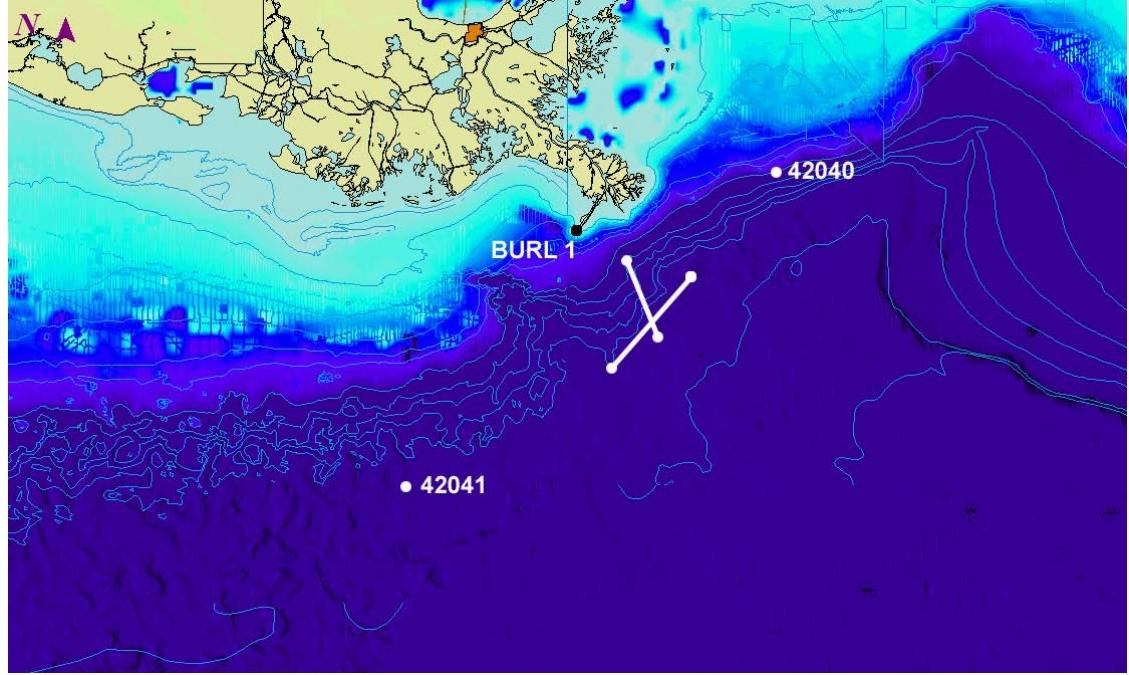


Fig. 1. LADC 01 and LADC 02 experiment location.

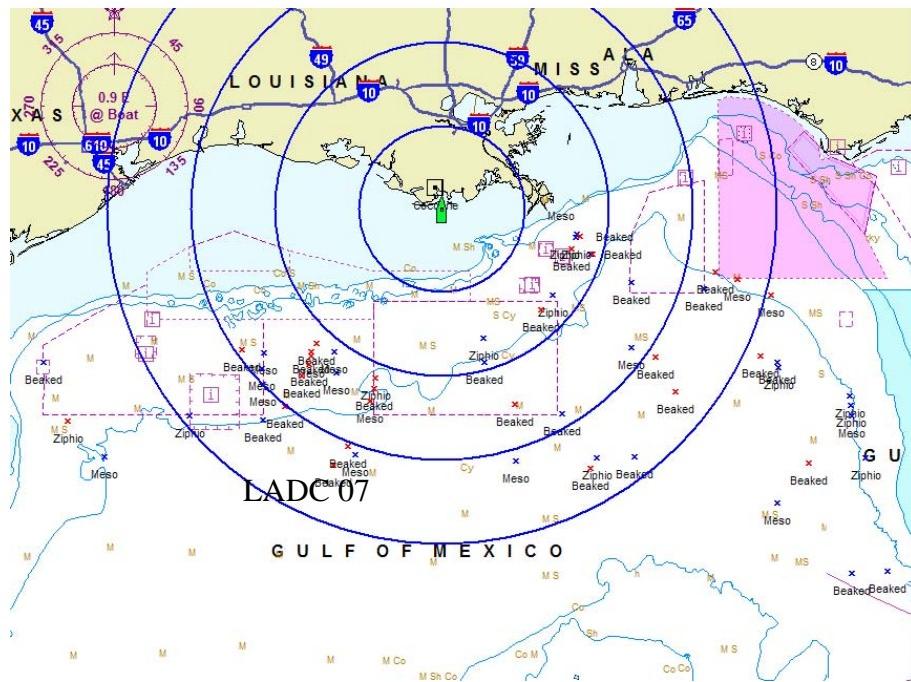


Fig. 2. LADC 07 location.

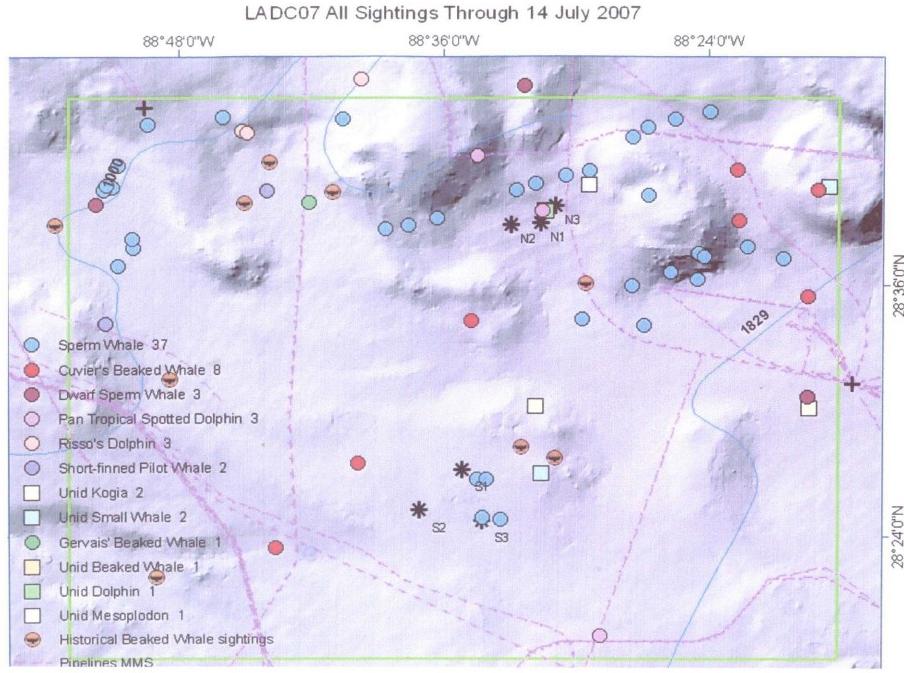


Fig. 3. Close-up of LADC 07 location and bathymetry. Six black stars are buoy positions.

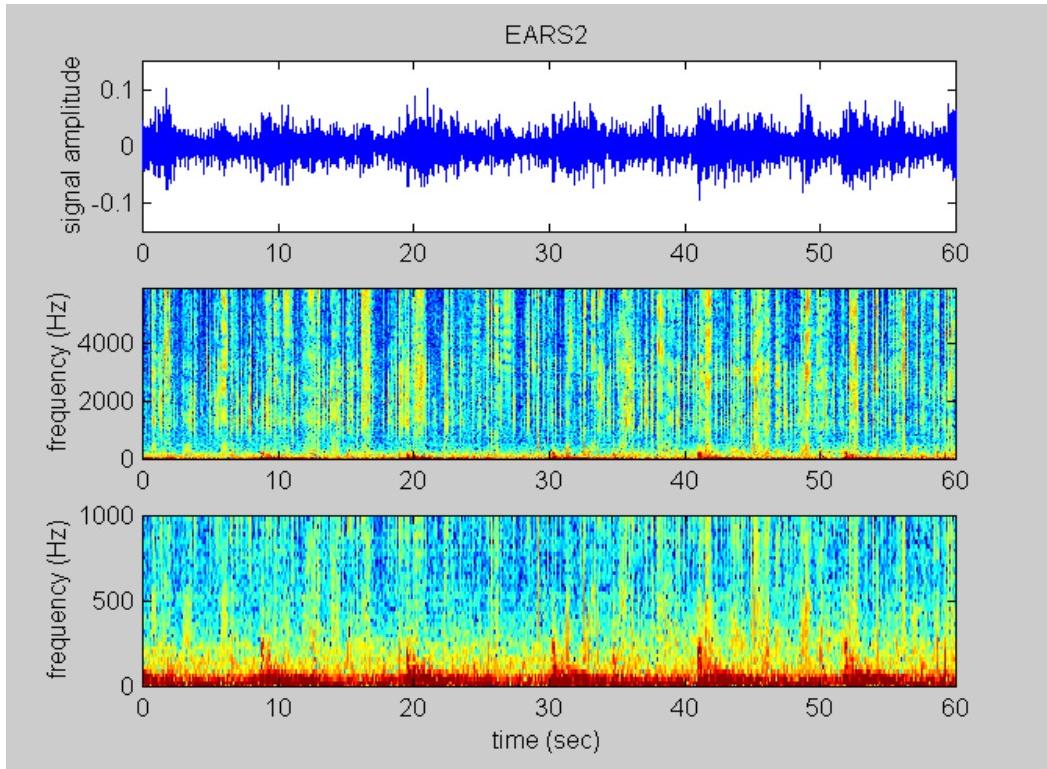


Fig. 4. Top: 800 m mooring data extracted from a 60 sec segment beginning at 2001 Julian Day 213 Zulu 0 hr, 9 min, 37 sec, voltage (proportional to pressure) amplitude versus time. Middle: Spectrogram of the 60-sec time series, frequencies up to 5859 Hz. Broadband transform lines are sperm whale clicks and closely spaced clicks are codas. Bottom: Same as middle spectrogram, frequencies up to 1000 Hz. Sperm whale clicks and codas can be seen, as well as low frequency seismic airgun shots (with reverberations) approximately every 11 sec. The airgun is 107 km away from the EARS buoy.

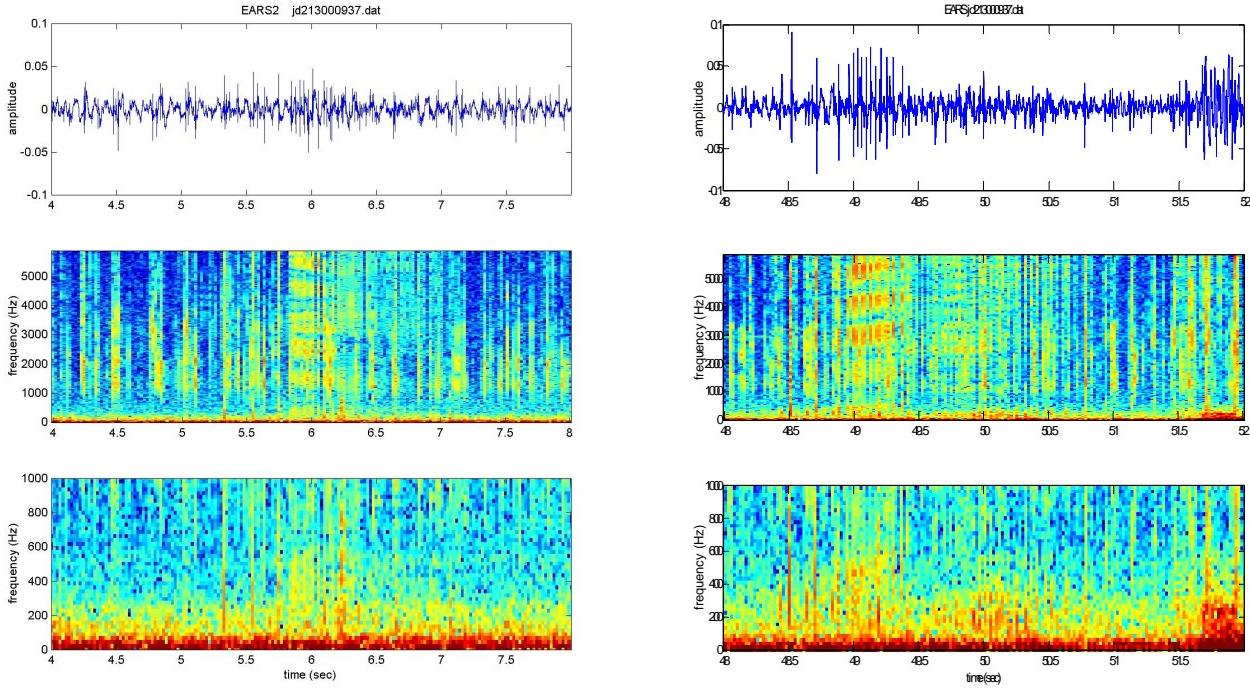


Fig. 5. Top, middle, and bottom: same as Fig. 4 but showing only 4 seconds. Left: 4 to 8 sec. Right: 48 to 52 sec.

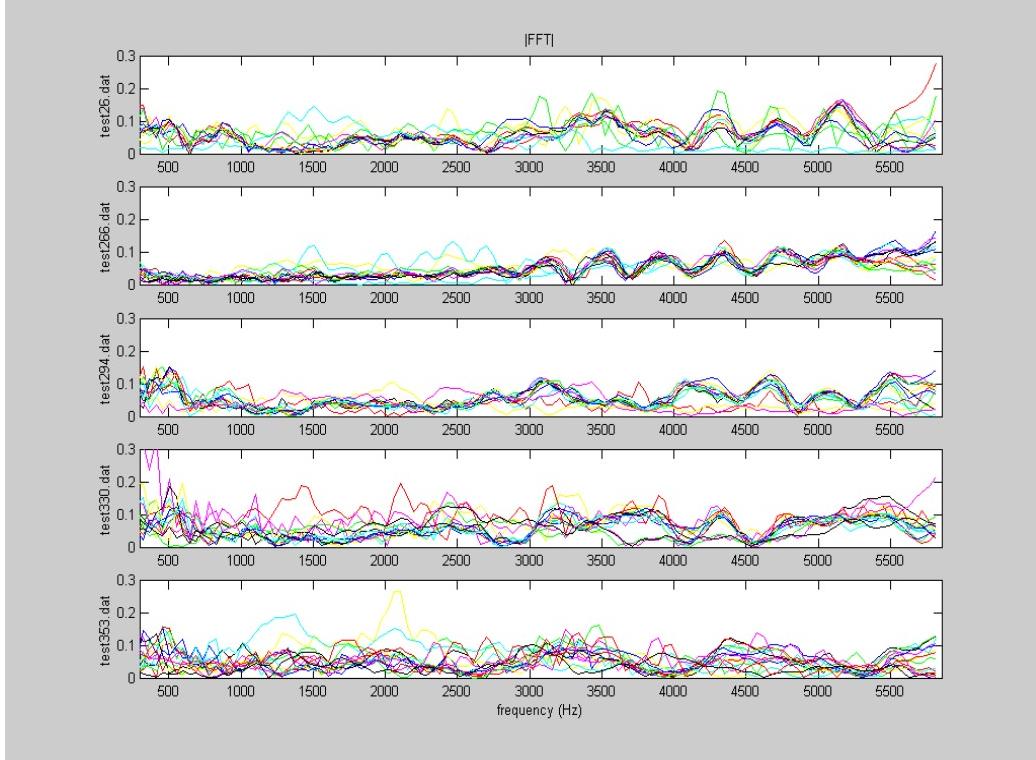


Fig. 6. Overplot of the magnitude Fourier spectra versus frequency for all the clicks in 5 sperm whale codas selected from Fig. 4. Each block is one coda, with individual clicks in each coda in a different color. Note that the shapes for the clicks in one coda are quite similar to each other, but distinctly different from those in other codas.

Fig. 6 shows an overplot of the magnitude Fourier spectra versus frequency for all the clicks in each of 5 sperm whale codas selected from Fig. 4. Notice that the spectral shapes of the clicks in one coda are similar to each other but can be different from

the shapes for other codas. Each coda plot can contain outliers that are likely to be echolocation clicks from other whales that occur during the time of the coda. Since the spectra for all clicks in a coda are similar, it follows that the time signal for all the clicks in a coda should be similar, and the graph in Fig. 7 confirms this by plotting the 12 clicks of one coda in a single graph with the zero offset so that the individual graphs may be viewed more easily.

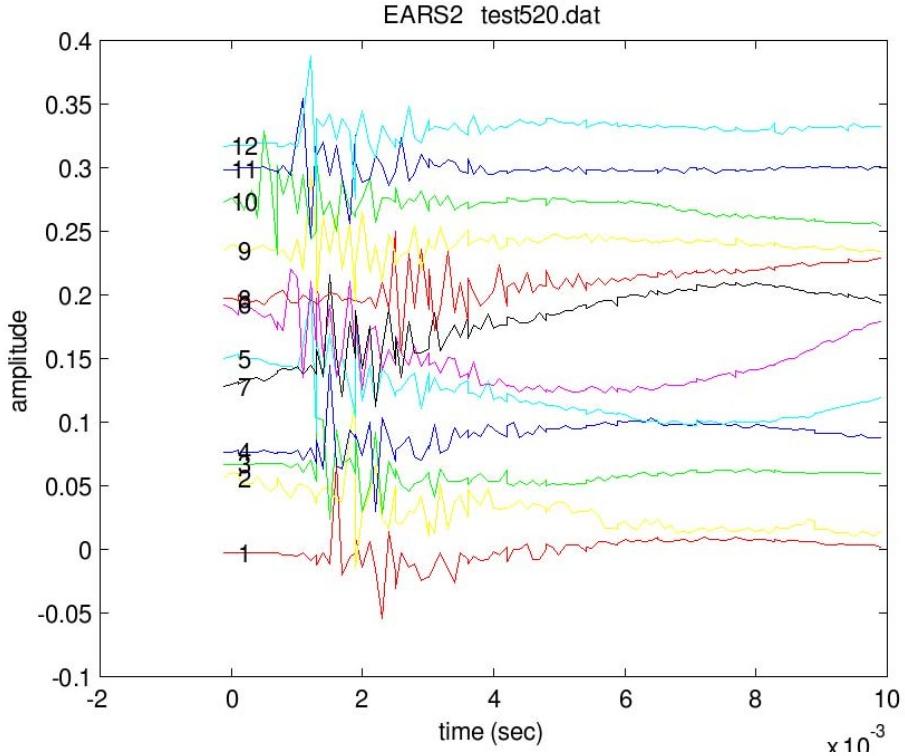


Fig. 7. Voltage amplitude versus time for all the clicks in one coda from Fig. 6 plotted versus time. Voltage in each click is offset for clarity.

Ongoing research to identify individual sperm and beaked whales from the properties of their echolocation and coda clicks using cluster analysis has been done by LADC. Although reasonably consistent and robust results showing distinct classes (each corresponding to an individual) have been obtained with both self-organizing maps (SOM) [14, 19] and K-means, no independent verification of these identifications has been available until recently. Data from a July 2007 experiment in the Gulf of Mexico is providing enough geometry information to verify some identifications. LADC deployed six EARS buoys measuring to 96 kHz for 9 days to record sperm and beaked whale clicks in the northern Gulf of Mexico. Three buoys were in close proximity (see Fig. 3) to enable multi-sensor detections of single clicks for possible localization, tracking, or bearing estimation sufficient to confirm the identification of individuals from cluster analysis [23, 28, 29]. Displays of cluster classifications versus time coupled with location estimates for the clicks give evidence of the accuracy of the identifications. Here, localization serves to verify the classification tool, although eventually click identification can complement localization by separating sounds from multiple sources when several whales' clicktrains overlap, potentially enabling tracking previously found impossible.

In Fig. 8 the results of self-organizing map cluster analysis for 46 sperm whale clicks measured in the LADC 07 experiment are compared to the localization results for the same 46 clicks. Even though these results are preliminary, there is 85% agreement in the identifications.

Rhythmic analysis of the sperm whale clicks, based on the Fourier transform, was previously reported in the literature as a tool for extracting the acoustic signature of individual sperm whales [22, 27]. A new approach, originating from the algorithm developed for the human motion analysis, was applied to study time-dependent periodicity in sperm whale signals recorded in the Gulf of Mexico. The new approach for rhythmic analysis of sperm whale echolocation clicks (used for navigation purposes) shows the presence of stable temporal periodicity that could possibly be attributed to the acoustic signature of individuals.

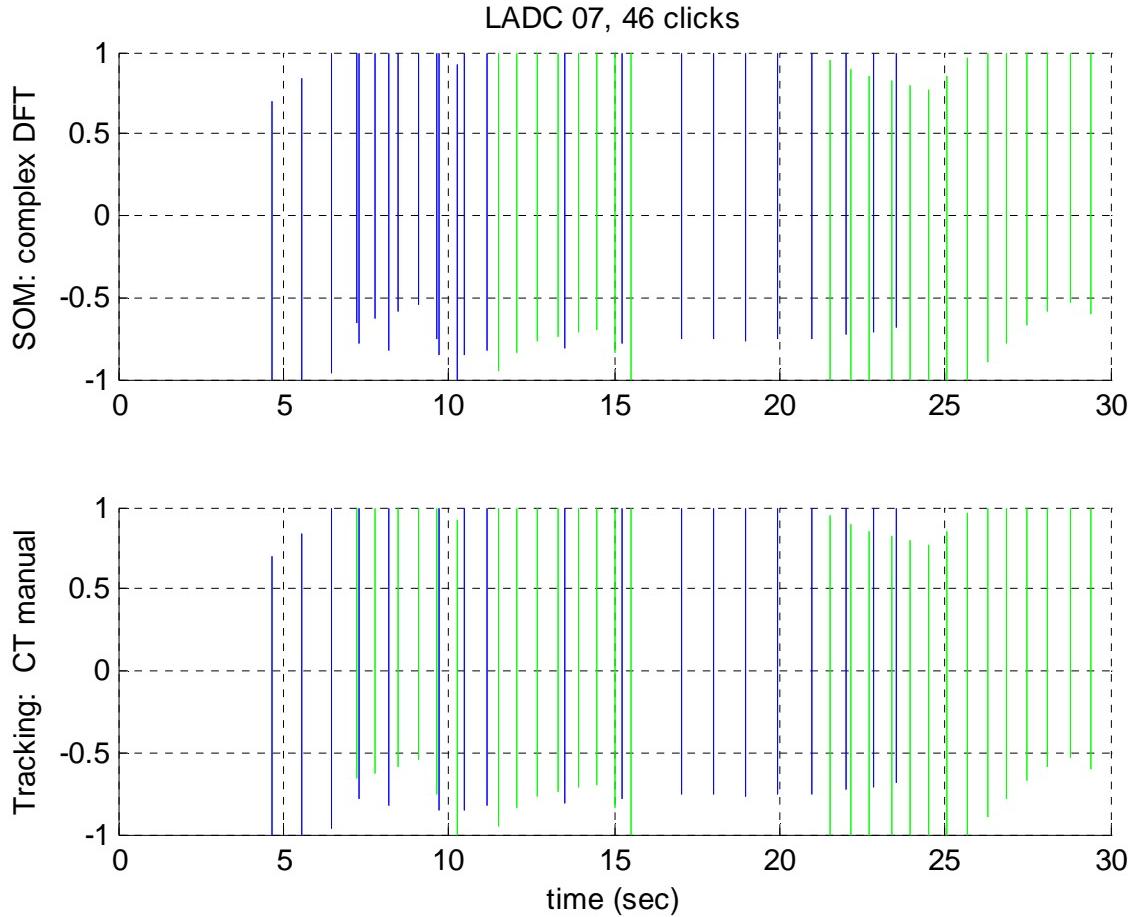


Fig. 8. Comparison of self-organizing map clustering method with manual localization. Two classes (two colors) representing two whales, with 85% agreement between the methods.

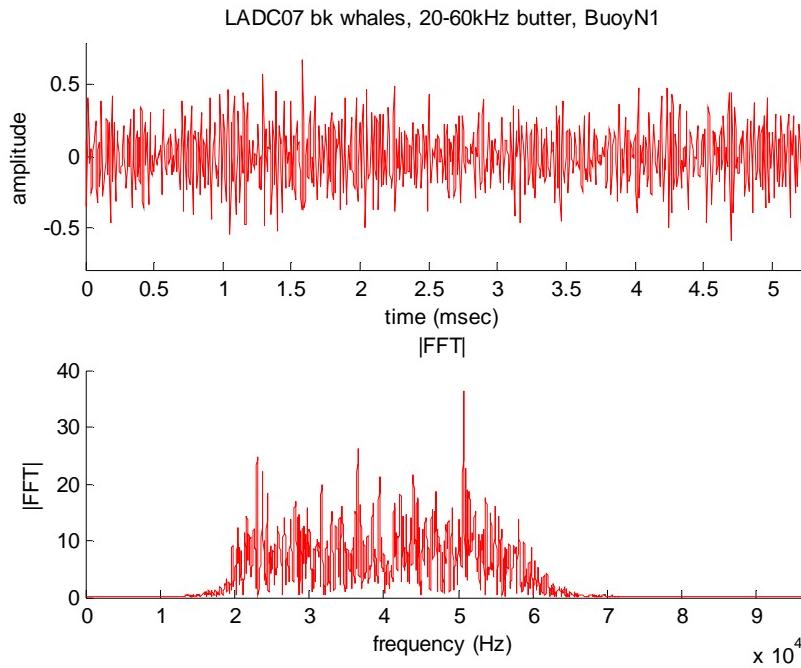


Fig. 9. Top: Amplitude versus time recorded on EARS buoy N1 in LADC 07, bandpass filtered from 20 to 60 kHz. Shown are assumed beaked whale clicks occurring in 52.1 msec. Bottom: Fourier magnitude spectrum of the top figure.

LADC 07 is believed to be the first acoustic detection of beaked whales in the Gulf of Mexico. The top plot of Fig. 9 shows the amplitude versus time signal bandpass filtered to contain between 20 and 60 kHz. This is the frequency band for the echolocation clicks of the beaked whale species studied by LADC thus far. The 52.1 msec of data appear to be quite rich in beaked whale clicks. The spectrum of this time signal is shown in the bottom plot. It represents an overplot of the spectra of the individual clicks. The general shape of the spectrum is consistent with beaked whale click spectra shown by others. Analysis of these echolocation clicks is ongoing.

III. KEY MARINE ANIMAL ACOUSTIC FINDINGS WITH EARS BUOYS

The following is a list of important findings obtained via the use of EARS buoys over the previous eight years:

1. Analysis of diurnal variations and the effects of shipping noise on sperm whale click rates.
2. First acoustic measurements of beaked whale clicks in the Gulf of Mexico.
3. High quality acoustic recordings of sperm whale codas that revealed similarities in the spectral properties of all the clicks in a coda. Subsequent analysis showed that all the individual click plots of pressure versus time and spectra for a single coda have similar character, which can be different from the character of the clicks in other codas. This suggests the possibility of identifying individual sperm whales from their coda click properties.
4. Measurements of echolocation clicks of both sperm and beaked whales (Cuvier's and Blaineville's) suggest the possibility of identifying individuals based on the properties of echolocation clicks.
5. Analysis of echolocation click rhythms suggests the possibility of isolating individual animals using rhythmic differences.
6. EARS measurements have made possible the combining of click property and rhythm analysis with whale localization for the verification of the identification and to assist in the tracking of multiple whales simultaneously.
7. Success with the combined rhythm analysis identification and tracking can enable passive marine mammal acoustic measurements to contribute significantly to behavioral studies and population assessments.

ACKNOWLEDGMENT

The authors gratefully acknowledge all individuals who made the experimental measurements possible, including those responsible for equipment design and fabrication, experimental planning, shipboard science, and ship crews.

REFERENCES

- [1] K. S. Norris and G. W. Harvey, "A theory for the function of the spermaceti organ of the sperm whale," *NASA SP-262*, pp. 397-417, 1972.
- [2] J. C. Gordon, "Evaluation of a method for determining the length of sperm whales from their vocalizations," *J. Zool.*, vol. 224, pp. 301-314, 1991.
- [3] A. M. Dougherty, 1999, "Acoustic Identification of Individual Sperm Whales (*Physeter macrocephalus*)," M.S. Thesis, University of Washington, 52 pages, 1999.
- [4] B. Mohl, M. Wahlberg, P. T. Madsen, A. Heerfordt, and A. Lund, "The monopulsed nature of sperm whale clicks," *J. Acoust. Soc. Am.*, vol. 114, pp. 1143-1154, 2003.
- [5] W. M. X. Zimmer, P. T. Madsen, V. Teloni, M. P. Johnson, and P. L. Tyack, "Off-axis effects on the multipulse structure of sperm whale usual clicks with implications for sound production," *J. Acoust. Soc. Am.*, vol. 118, pp. 3337-3345, November 2005.
- [6] J. Newcomb, R. Fisher, A. Turgut, R. Field, G. Ioup, J. Ioup, G. Rayborn, S. Kuczaj, J. Caruthers, R. Goodman, and N. Sidorovskaia, "Modeling and Measuring the Acoustic Environment of the Gulf of Mexico," invited, *Proceedings of the Information Transfer Meeting of the Minerals Management Service*, pp. 509-521, invited January 2002.
- [7] J. Newcomb, R. Fisher, R. Field, A. Turgut, G. Ioup, J. Ioup, G. Rayborn, S. Kuczaj, J. Caruthers, R. Goodman, and N. Sidorovskaia, "Near-bottom hydrophone measurements of ambient noise and sperm whale vocalizations in the northern Gulf of Mexico," *J. Acoust. Soc. Am.*, vol. 111, pp. 2371, June 2002.
- [8] J. Newcomb, R. Fisher, R. Field, G. Rayborn, S. Kuczaj, G. Ioup, J. Ioup, A. Turgut, "Measurements of Ambient Noise and Sperm Whale Vocalizations in the Northern Gulf of Mexico Using Near Bottom Hydrophones," *Proceedings of the MTS/IEEE OCEANS2002*, pp. 1365-1371, October 2002.
- [9] N. A. Sidorovskaia, G. E. Ioup, J. W. Ioup, and J. W. Caruthers, "Acoustic propagation studies for sperm whale vocalization analysis during LADC experiments," *High-Frequency Ocean Acoustics*, M. B. Porter, M. Siderius, and W. A. Kuperman, editors, AIP Conference Proceedings, pp. 288-295, March 2004.
- [10] J. Newcomb, R. Fisher, R. Field, G. Ioup, J. Ioup, J. Larue, G. Rayborn, S. Kuczaj, J. Caruthers, R. Goodman, C. Walker, R. Paulos, J. Ramos, R. Thames, S. Vinogradov, N. Sidorovskaia, I. Udvodchenkov, I. Rypina, and M. Snyder, "Using Acoustic Buoys to Assess Ambient Noise and Sperm Whale Vocalizations," invited, *Proceedings of the Information Transfer Meeting of the Minerals Management Service*, pp. 269-276 and 578-588, 2004.

- [11] G. E. Ioup, J. W. Ioup, J. P. Larue, N. A. Sidorovskaia, S. A. Kuczaj, G. H. Rayborn, and C. D. Walker, "Spectrogram analysis of low to mid frequency marine mammal clicks," *J. Acoust. Soc. Am.*, vol. 115, pp. 2556, May 2004.
- [12] N. A. Sidorovskaia, I. A. Udovydchenkov, I. I. Rypina, G. E. Ioup, J. W. Ioup, J. W. Caruthers, J. Newcomb, and R. Fisher, "Propagation modeling for sperm whale acoustic clicks in the northern Gulf of Mexico," *J. Acoust. Soc. Am.*, vol. 115, pp. 2556, May 2004.
- [13] J. Larue, G. E. Ioup, and J. W. Ioup, "Detecting sperm whale clicks in the presence of ambient and shipping noise using higher order moments," *J. Acoust. Soc. Am.*, vol. 115, pp. 2487, May 2004.
- [14] J. W. Ioup and G. E. Ioup, "Sperm whale identification using self organizing maps," *J. Acoust. Soc. Am.*, vol. 115, pp. 2556, May 2004.
- [15] N. A. Sidorovskaia, G. E. Ioup, and J. W. Ioup, "Studies of waveguide propagation effects on frequency properties of sperm whale communication signals," *J. Acoust. Soc. Am.*, vol. 116, pp. 2614, November 2004.
- [16] G. E. Ioup, J. W. Ioup, N. A. Sidorovskaia, R. T. Walker, S. A. Kuczaj, C. D. Walker, G. H. Rayborn, B. Brack, A. Wright, J. Newcomb, and R. Fisher, "Analysis of Bottom-Moored Hydrophone Measurements of Gulf of Mexico Sperm Whale Phonations," invited, *MMS 2005-066 – Proceedings: 23rd Annual Gulf of Mexico Information Transfer Meeting*, pp. 109-136, January 2005.
- [17] N. A. Sidorovskaia, A. Tashmukhambetov, G. E. Ioup, J. W. Ioup, J. J. Newcomb, J. M. Stephens, C. D. Walker, and G. H. Rayborn, "Littoral Acoustic Demonstration Center: Experimental and Modeling Capabilities for Assessment of the Environmental Impact of Acoustic Sources in the Gulf of Mexico," invited, *Proceedings of the 9th World Multiconference on Systemics, Cybernetics and Informatics (WMSCI 2005)*, vol. IX, pp. 113-114, July 2005.
- [18] N. A. Sidorovskaia, B. Richards, G. E. Ioup, and J. W. Ioup, "Spectral identification of sperm whales from Littoral Acoustic Demonstration Center passive acoustic recordings," *J. Acoust. Soc. Am.*, vol. 118, pp. 2001, October 2005.
- [19] J. W. Ioup and G. E. Ioup, "Identifying individual sperm whales acoustically using self-organizing maps," *J. Acoust. Soc. Am.*, vol. 118, pp. 2001, October 2005.
- [20] G. E. Ioup, J. W. Ioup, L. A. Pflug, A. M. Tashmukhambetov, and N. A. Sidorovskaia, "Acoustic identification of beaked and sperm whales," *J. Acoust. Soc. Am.* 122, pp. 3003, December 2007
- [21] G. E. Ioup, J. W. Ioup, L. A. Pflug, A. M. Tashmukhambetov, N. A. Sidorovskaia, C. H. Thompson, and C. O. Tiemann, "Identifying individual clicking whales acoustically amid the clutter of other clicking whales," invited, *J. Acoust. Soc. Am.*, vol. 124, pp. 2500, November 2008
- [22] N. A. Sidorovskaia, P. Schexnayder, A. Ekimov, J. Sabatier, G. E. Ioup, and J. W. Ioup, "Rhythmic analysis of sperm whale broadband acoustic signals," *J. Acoust. Soc. Am.*, vol. 125, pp. 2738, May 2009.
- [23] J. W. Ioup, G. E. Ioup, L. A. Pflug, A. M. Tashmukhambetov, C. O. Tiemann, A. Bernstein, N. A. Sidorovskaia, P. Schexnayder, J. J. Newcomb, S. A. Kuczaj, G. H. Rayborn, and R. M. Carlson, "Localization to verify the identification of individual sperm whales using click properties," *J. Acoust. Soc. Am.*, vol. 125, pp. 2616, May 2009.
- [24] G. E. Ioup, J. W. Ioup, A. M. Tashmukhambetov, L. A. Pflug, J. J. Newcomb, N. A. Sidorovskaia, S. A. Kuczaj, G. H. Rayborn, J. M. Stephens, C. O. Tiemann, and A. Bernstein, "Environmental acoustic recording system (EARS) buoys for marine animal acoustics," invited, *J. Acoust. Soc. Am.*, vol. 125, pp. 2616, May 2009.
- [25] N. Sidorovskaia, P. Schexnayder, G. E. Ioup, J. W. Ioup, C. O. Tiemann, J. Sabatier, and A. Ekimov, "Integrated passive acoustic approach for detection, localization, and identification of individual marine mammals as applied to workshop data," *Proceedings of the 4th International Workshop on Detection, Classification and Localization of Marine Mammals Using Passive Acoustics*, September 2009.
- [26] G. E. Ioup, J. W. Ioup, L. A. Pflug, C. O. Tiemann, A. Bernstein, and N. A. Sidorovskaia, "Identifying individual clicking whales acoustically I. From click properties," invited, *J. Acoust. Soc. Am.*, October 2009.
- [27] N. A. Sidorovskaia, P. Schexnayder, G. E. Ioup, J. W. Ioup, C. O. Tiemann, A. Bernstein, A. Ekimov, and J. Sabatier, "Identifying individual clicking whales acoustically II: From click rhythms," invited, *J. Acoust. Soc. Am.*, October 2009.
- [28] C. O. Tiemann, A. M. Thode, J. Straley, V. O'Connell, and K. Folkert, "Three-dimensional localization of sperm whales using a single hydrophone," *J. Acoust. Soc. Am.* **120** (4), 2355-2365.
- [29] C. O. Tiemann, "Three-dimensional single-hydrophone tracking of a sperm whale demonstrated using workshop data from the Bahamas," *Canadian Acoustics* **36** (1), 67-73.